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PAPER

Experimental Investigation of Propagation Characteristics and Performance of 2.4-GHz ISM-Band Wireless LAN in Various Indoor Environments

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SUMMARY Wireless communication systems are affected by several factors in the indoor environment. The complexity of this environment, however, has hampered the development of methods for analyzing it. Reported here is our investigation of the relationship between the propagation characteristics and performance of a 2.4-GHz ISM-band wireless LAN in various indoor environments. Our objective was to develop guidelines for designing ideal indoor environments for wireless LANs. A booth constructed of a ceiling, floor, and wall materials that could be changed was used for our investigation. The transmission loss and delay spread were measured for four environments; they were calculated by using a ray-tracing method to verify the effectiveness of the ray tracing calculation. The throughput and BER characteristics were measured for the same environments. The following results were obtained. (1) The transmission loss and delay spread could be estimated by using this ray tracing method because the deviations between the calculated and measured data were within 5 dB for the transmission loss and within 10 ns for the delay spread. (2) Reflections from the walls caused a serious interference problem: throughput was 0.0 at more than 30% of the positions along the center line of the booth when the walls were constructed of high-reflection-coefficient material. (3) The throughput and BER were closely correlated with the delay spread; the number of positions meeting a certain throughput was estimated by the method based on the delay spread calculated using the ray tracing method. It was within 10% of the number measured. The results obtained can be used to design ideal indoor environments for 2.4-GHz ISM-band LAN systems.

key words: *propagation characteristic, delay spread, indoor environment, multipath, 2.4-GHz ISM-band wireless LAN, throughput, BER*

1. Introduction

Several kinds of wireless communication systems, such as wireless local area networks (LANs) and cordless phones, are now used in many offices. However, if the system is large and complex, electromagnetic interference with other systems may occur [1], [2].

Various types of electromagnetic interference have been studied, including the effect of the waves generated by a microwave oven on the performance of a wireless system [3], [4]. Improvements in the antenna system [5] and the signal-processing system [6] have helped to eliminate electromagnetic interference. Another approach is to choose suitable building materials and position them appropriately so as to eliminate interference. Some researchers have studied the propagation characteristics and performance of wireless systems in buildings [7]. In particular, a method for positioning suitable materials has been found effective for 2.4-GHz ISM-band wireless LAN systems [8], [9]. These systems are finding increasing use in many offices because of their flexibility. However, both designers of buildings and wireless LAN systems need to know the relationship between the performance of 2.4-GHz ISM-band wireless LAN systems and their indoor environments, and this relationship has not been sufficiently clarified.

Investigating the propagation characteristics and performance of 2.4-GHz ISM-band wireless LAN systems in an indoor office environment is of course best done in an actual office. However, this is difficult because a typical office is subjected to many types of electromagnetic waves, such as those radiated from electrical equipment and wireless communication devices. Moreover, the effect of various building materials on the propagation characteristics is difficult to investigate in an actual office. Verification of the measured results by simulation is difficult as well because the office structure tends to be complex. Therefore, we need an experimental environment that functions both as an anechoic chamber and as a typical office and that has a simple structure to enable the propagation characteristics to be calculated.

We have investigated the propagation characteristics and performance of a 2.4-GHz ISM-band wireless LAN in various indoor environments. Our goal was to develop guidelines for designing ideal indoor environments for wireless LANs. We used a booth whose building materials could be changed and that blocked all electromagnetic waves present in the external environment. We measured the transmission loss and delay spread for four different environments, which were constructed by changing the wall and floor materials. These propagation characteristics were also calculated by using a ray tracing method to verify the effectiveness of the ray tracing calculation. We measured the throughput and bit error rate (BER) characteristics of the wireless LAN in order to determine the relationship between the performance of the wireless LAN and the indoor environment. Furthermore, we derived a method for estimating the throughput characteristics that uses the calculated delay spread.

2. Structure of Booth

We constructed a booth (Fig. 1) that enabled the building materials to be easily changed. It had a simple structure to

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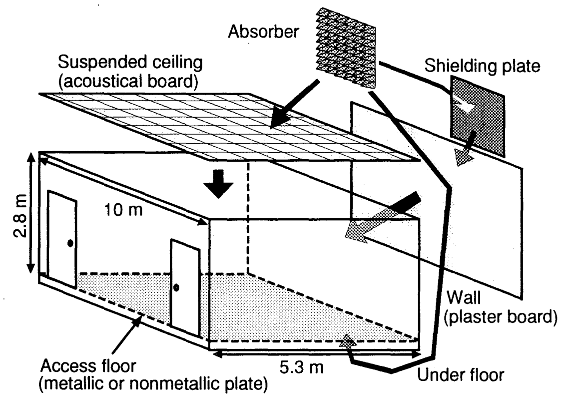


Fig. 1 Structure of booth used for measurement.

Table 1 Building materials for indoor environments 1 through 4.

Env.	Ceiling	Walls	Floor
1	2-cm-thick acoustical squares	1.25-cm-thick plaster boards	2.5-cm-thick nonmetallic plates
2	2-cm-thick acoustical squares	1.25-cm-thick plaster boards	2-mm-thick metallic plates
3	2-cm-thick acoustical squares	1-mm-thick metallic plates	2.5-cm-thick nonmetallic plates
4	2-cm-thick acoustical squares	1-mm-thick metallic plates	2-mm-thick metallic plates

enable the propagation characteristics to be calculated. The booth was completely enclosed with electromagnetic absorbers to prevent intrusion of radio waves with the same frequency bands used in our investigation. The absorbers had a reflection loss above 20 dB for radio waves above 1.5 GHz. The booth was 10 m long, 5.3 m wide, and 2.8 m high and had two metal doors. The materials of the floor, ceiling, and walls were easy to change; it took about two hours to change the floor material and about four hours to change the wall and ceiling materials.

We constructed four different environments by using the materials listed in Table 1. The suspended ceiling was constructed of acoustical squares (0.9 × 0.9 m, 2 cm thick) made of rock wool and was fixed. The raised access floor was constructed of either metallic or nonmetallic plates (0.5 × 0.5 m). The walls were constructed as is typical in Japanese offices; steel beams were raised at 0.5-m intervals and plaster boards were affixed to both sides of the beams. To simulate metallic walls, which are also common in Japanese offices, metallic plates were affixed to the plaster boards.

3. Propagation Characteristics

3.1 Measurement Method

The setup for measuring the propagation characteristics of the 2.4-GHz ISM-band wireless LAN in the four environments is shown in Fig. 2. Monopole antennas, attached to an actual wireless LAN system, were used for transmission and

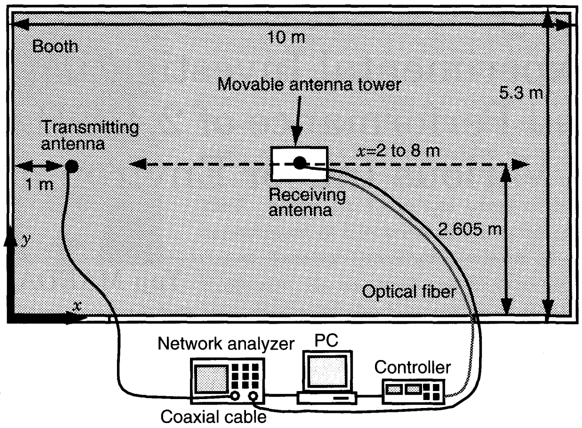


Fig. 2 Setup for measuring propagation characteristics.

reception. The transmitting antenna was placed on the center line (y=2.605 m) of the booth at x=1 m. The receiving antenna was mounted on a movable antenna tower, which was positioned on the center line and moved 2 cm at a time, from x=2 to x=8 m. Because the effect of the reflected waves was the strongest along the center line of the booth, both antennas were placed on the center line. The antenna tower was connected to the controller by an optical fiber and operated using a personal computer. The height of both antennas was 1 m. A network analyzer was used to simultaneously measure the transmission loss and delay profile.

3.2 Calculation Method

Ray tracing based on geometrical optics algorithms can be used to predict propagation characteristics. We calculated the propagation characteristics by using the ray launching method [10], [11]. This method allows easier calculation in complex environments, such as our simulated electromagnetic environment of an actual office.

Rays were projected from a source with angular spacing α defined by considering the calculation accuracy and calculation time and typically set at $\alpha \leq 1^\circ$ [11]. We set $\alpha = 0.2^\circ$. We used a reception sphere [11] at the receiving position; rays that passed through the sphere were treated as received rays. The radius of the sphere was set within $\alpha l / \sqrt{3}$ [11], with l as the distance between the transmitting and receiving points. The measured antenna patterns and the measured gain of the transmitting and receiving antennas were also used in our calculation.

The refractive index (n) of the materials we used was measured at 2.484 GHz in an anechoic chamber by using a network analyzer and the time-domain function [12]. It was defined as $n = \sqrt{\mu_r \varepsilon_r}$ for rays incident to the material (relative permeability of μ_r and relative permittivity of ε_r) from free space. The real part of the index affects the amplitude of the reflected and transmitted waves, and its imaginary part affects the phases of those waves. It was not determined by the incident angle but by the quality of the material because we assumed that all the materials had uniform refractive indexes and flat surfaces. The n of the rock wool used in the

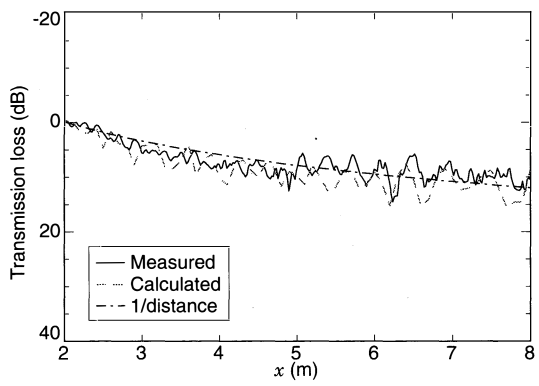


Fig. 3 Transmission loss for environment 1.

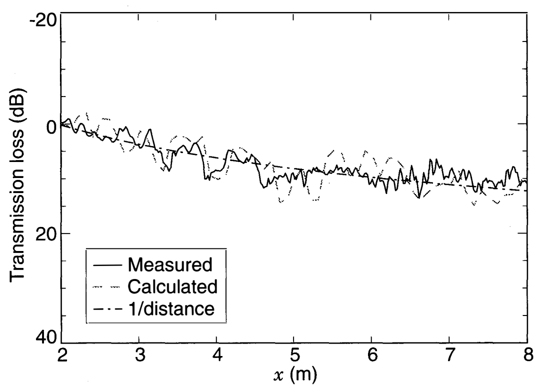


Fig. 4 Transmission loss for environment 2.

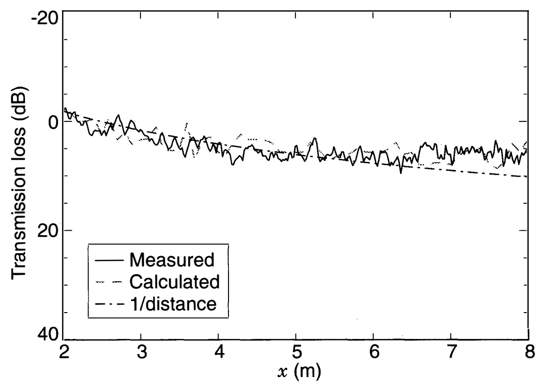


Fig. 5 Transmission loss for environment 3.

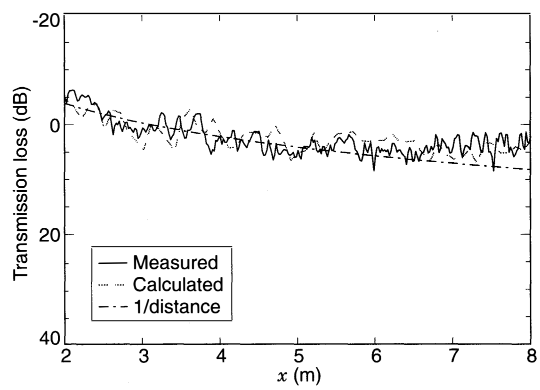


Fig. 6 Transmission loss for environment 4.

suspended ceiling was 1.7–j0.2, and the n of the plaster boards used for the walls was 1.9–j0.2. The n of the nonmetallic plates, which was made of sand ash, pumice, and glass fibers, used for the floor was 2.8–j0.2. The metallic plates used for the floor and the plaster boards used for the wall were considered to be perfect conductors.

3.3 Transmission Loss

The measured and calculated transmission losses for the four environments are shown in Figs. 3 through 6. The transmission loss of each was normalized using the value at x=2 m in environment 1. A line that decreases in inverse proportion to the distance between the transmitting and receiving antennas and is fitted to the loss measured at x=2 m is also shown in each figure. Because the monopole antenna of a wireless LAN is usually used with vertical polarization, we considered only vertical polarization. The average power of the frequency band (2.471 to 2.497 GHz) is important [13], [14] in the direct sequence spread spectrum (DSSS) system used in a wireless LAN system. Furthermore, it is difficult to evaluate the relationship between the transmission loss and indoor environment for each frequency in the band because the loss varies widely. Accordingly, in estimating the average power, we used the average transmission loss for 401 frequencies between the lowest and the highest frequencies in the band.

For nonmetallic wall environments 1 and 2 (Figs. 3 and 4), it roughly decreased in inverse proportion to the distance. On the other hand, for metallic wall environments 3 and 4 (Figs. 5 and 6), the transmission loss roughly decreased in inverse proportion to the distance only up to about x=6.5 m, then decreased very little. These results show that the strength of the electric field at x>6.5 m at the centerline was almost the same when the walls were made of high-reflection-coefficient material, because the reflections from the walls were strong. Moreover, although the electric field strength for the nonmetallic wall environments (1 and 2) was almost the same at x=2 and 8 m, for the metallic wall environments (3 and 4), it was generally greater than for the nonmetallic wall environments. Particularly for environment 4 at x=2 m, it was about 4 dB greater than for environment 1; for environment 4 at x=8 m, it was about 8 dB greater than for environment 1.

The calculated results agreed with the measured ones within 5 dB for all of the environments. This indicates that the ray tracing method can be used to estimate the transmission loss.

3.4 Delay Profile

Studies of outdoor radio-wave propagation have shown that the power delay profile is closely related to the performance of a wireless system [15]. The power delay profiles calculated using the ray tracing method for environments 1 and 3 are shown in Figs. 7 and 8, respectively. The difference be-

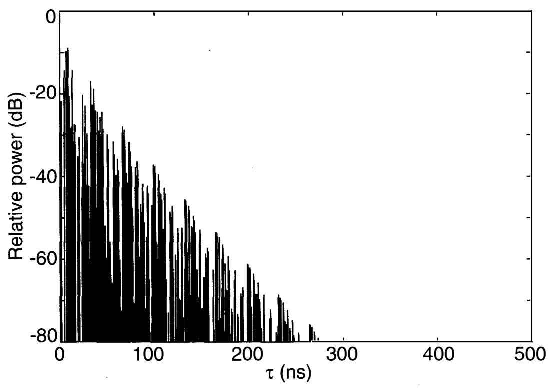


Fig. 7 Calculated rms delay profile for environment 1 at x=5 m.

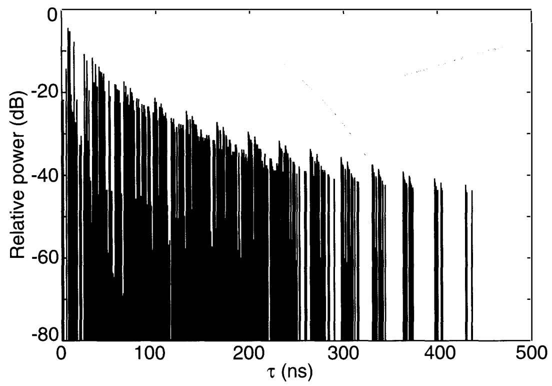


Fig. 8 Calculated rms delay profile for environment 3 at x=5 m.

tween these two environments was the wall material. These delay profiles were calculated at about the center of the booth (x=2.605 m, y=5 m, and z=1 m). In these figures, the vertical axes show the relative power, and the horizontal axes show the delay times; the ray at τ=0 is the direct wave.

As shown in Figs. 7 and 8, rays reflected once at the floor, ceiling, or walls arrived within about 10 ns of the direct ray's arrival. This is because the difference in the propagation distances between the direct ray and a one-time-floor-reflected ray was 0.47 m, a one-time-ceiling-reflected ray was 1.38 m, a one-time-wall-reflected ray at x=0 m was 2 m, and a one-time-wall-reflected ray at y=0 and 5.3 m was 2.64 m. The corresponding τ's were 1.6, 4.6, 6.7, and 8.8 ns. We found that the highest power level (excluding that of the direct ray) was reached by the rays reflected by the walls. Comparison of these two delay profiles clearly shows that the strength of the strongly reflected rays weakened rapidly when the low-reflection-coefficient wall material was used (environment 1), while they weakened only a little when the high-reflection-coefficient wall material was used (environment 3), because very little attenuation occurs in reflections from high-reflection-coefficient walls for a vertical polarization. Moreover, the average delay was 4.9 ns and the root mean-square (rms) delay spread was 10.3 ns for environment 1 (Fig. 7), while the average delay was 24.6 ns and the rms delay spread was 39.6 ns for environment 3 (Fig. 8). These values reflect the differences in effect of the waves reflected from the walls.

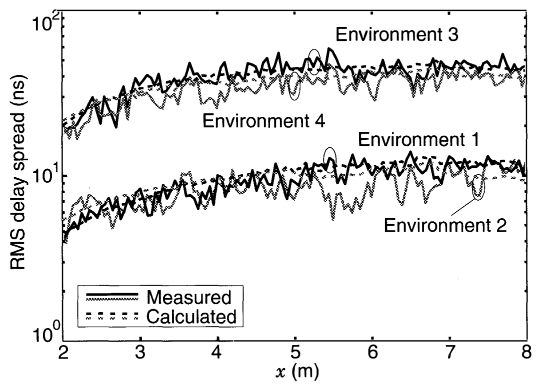


Fig. 9 RMS delay spread for environments 1 through 4.

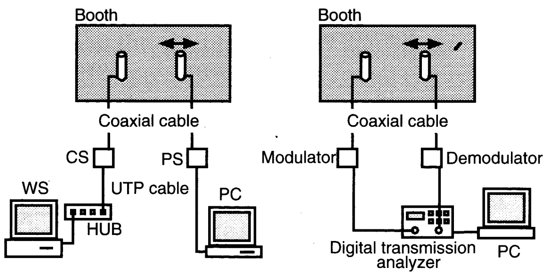
The rms delay spread is an important parameter [15] in evaluating the power delay profile. The measured and calculated delay spreads for the four environments are shown in Fig. 9. In the measurements, the delay profile was measured up to 500 ns, and the delay spread was evaluated with the noise floor of the system at –40 dB. The vertical axis shows the delay spread, and the horizontal axis shows the position of the receiving antenna. The delay spreads varied widely with the wall material. The average difference in the spread between 2 and 8 m for the two wall materials (comparing environments 1 with 3 and 2 with 4) was about 40 ns. In comparison, the average difference with differing floor materials (comparing 1 with 2 and 3 with 4) was within about 10 ns. The delay spread was the highest for environment 3. These results show that the delay spread is a more precise indicator of the relationship between the propagation characteristics and the indoor environment than is the transmission loss. This is because the differences in transmission loss between environments were within about 8 dB, while the differences in delay spread were about 40 ns.

The deviation between the calculated and measured values was within about 10 ns for all cases. And as discussed in the previous section, the calculated transmission loss agreed with the measured one within 5 dB. These results indicate that the propagation characteristics, such as transmission loss and delay spread, can be estimated by using the ray tracing method.

4. Performance of Wireless LAN

4.1 Measurement Method

Figure 10 shows the setups we used to measure the performance of the 2.4-GHz ISM-band wireless LAN system. Figure 10(a) shows the setup for measuring throughput, and Fig. 10(b) shows that for measuring the BER characteristics. An actual wireless LAN system was used for the throughput measurements. This setup used a standard DSSS system for modulation. The operating frequency in Japan [8], [9] is 2.471 to 2.497 GHz. The center frequency is 2.484 GHz, and the spread bandwidth is 26 MHz. The data rate of this system is 2 Mbps. Throughput was measured by transferring a 5-MB



(a) Throughput (b) BER

Fig. 10 Setup for measuring performance of wireless LAN.

text file using the file transfer protocol from a center station (CS) to a personal station (PS). We used a DSSS system developed by our laboratory to measure the BER because it is difficult to measure the BER of an actual wireless LAN. In both the throughput and BER measurements, vertically polarized monopole antennas were attached to the actual wireless LAN and used as the transmitting and receiving antennas. These antennas were placed at the same positions as for the propagation characteristics measurement (setup shown in Fig. 2).

4.2 Throughput Characteristics

The measured throughput characteristics are shown in Fig. 11. The throughput was normalized using the throughput measured when a CS was directly connected to a PS by a coaxial cable instead of by using antennas. The vertical axis shows the percentage of measurement positions (x=2 to 8 m) at which the throughput was at or above the value shown on the horizontal axis. The throughput values for environments 1 and 2 were almost the same, reaching 1.0 at about 95% of the receiving positions. For environments 3 and 4, however, there was a clear distinction as to the positions where communication was effective. The throughput was 1.0 at about 35% of the positions and close to 0.0 at about 60% of the positions for environment 3. For environment 4, the throughput was 1.0 at about 60% of the positions and close to 0.0 at about 30% of the positions.

The throughput characteristics at each receiving position for environment 3, the worst case, are shown in Fig. 12. The vertical axis is the normalized throughput, and the horizontal axis is the receiving position. The throughput was almost 1.0 at x=2.4 m; it was 0.0 at around the center of the booth (x=5 m); and it was 0.0 or 1.0 at other positions that were several centimeters apart. This result shows that the throughput has a polar characteristic and that its value changes at intervals of several cm when the walls are made of a high-reflection-coefficient material like metallic plates.

These results show that a wireless LAN can have good throughput and effective operation at most positions when room materials are selected for optimum effect. Walls of a low-reflection-coefficient material like plaster yielded good results, while the throughput decreased with walls of high-reflection-coefficient material like metal. However, the percentage of zero-throughput positions was less for metallic floors than for nonmetallic floors. This counterintuitive result may be because the antennas were placed along the centerline of the booth, where the interference caused by waves reflected from the walls was strongest. It may be that the strong reflected waves from the metallic floor canceled out some of this interference.

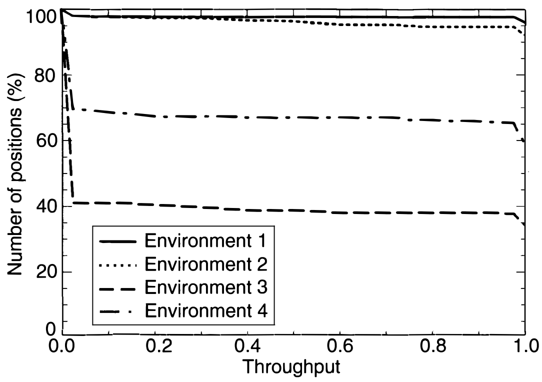


Fig. 11 Throughput characteristics of wireless LAN for environments 1 through 4.

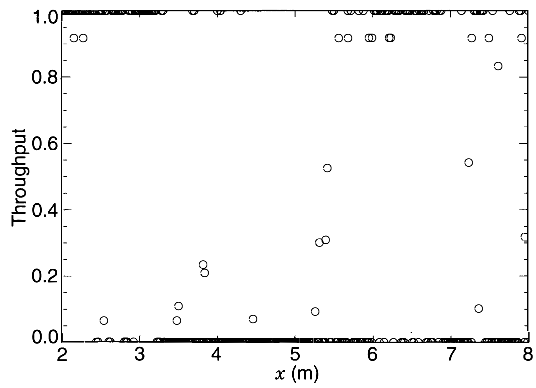


Fig. 12 Throughput characteristics at each receiving position for environment 3.

4.3 BER Characteristics

The measured BER characteristics are shown in Fig. 13. The vertical axis shows the percentage of measurement positions (x=2 to 8 m) at which the BER was at the value shown on the horizontal axis. The BER for environments 1 and 2 ranged mostly between 10^{-5} and 10^{-3}. In comparison, the BER for environments 3 and 4 was distributed mainly between 10^{-3} and 10^{-2}. Most of the BER values for environment 3 were distributed around 10^{-2}. These results show that the BER variation tends to be similar to the throughput variation because the result for environment 1 was almost the same as it was for environment 2 and the result for environment 3 was almost the same as it was for environment 4.

Figure 14 shows the relationship between the BER and the throughput for all environments. The BER corresponds to the throughput measured at the same point. The average

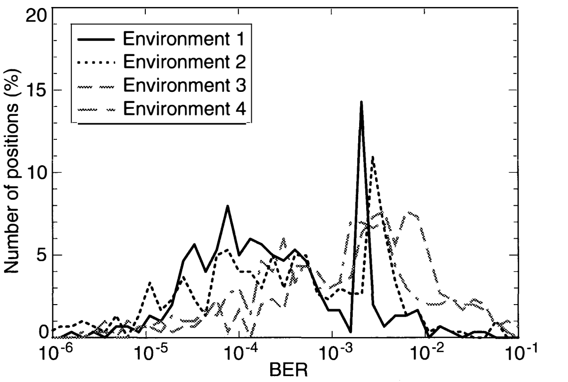


Fig. 13 BER characteristics of DSSS system for environments 1 through 4.

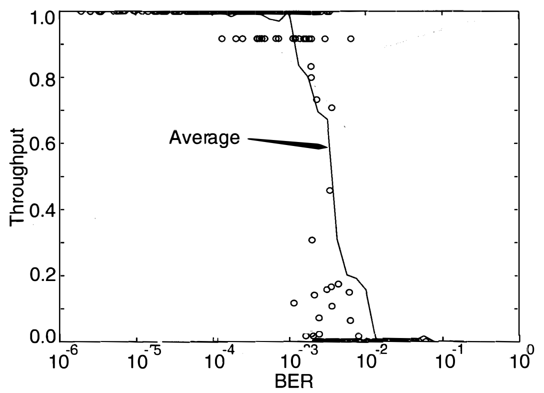


Fig. 14 Throughput and BER characteristics for environments 1 through 4.

throughput for each BER is also shown. The throughput changes between BERs of 10^{-4} and 10^{-2} and is almost 1.0 when the BER is below 10^{-4}. The average throughput decreases when the BER reaches 10^{-3}.

5. Evaluation of Wireless LAN's Performance

We calculated the throughput by using the calculated and measured delay spread and the BER and compared these results with the measured ones.

For a signal modulated by quadrature phase-shift keying (QPSK), the relationship between the average irreducible BER, P_b, and the rate of delay spread, t_d, for bit period, t_p, can be written as [15]:

$$P_b = 10^{\left(1.83\log\left(t_d / t_p\right) - 0.98\right)} \tag{1}$$

The wireless LAN system we used in our measurements uses the baseband modulation of differential QPSK (DQPSK) and has a data rate of 2 Mbps and a bit period of 500 ns. The delay spread is obtained from calculation or measurement. Although there are some differences between QPSK and DQPSK, the average irreducible BER for a wireless LAN is estimated by using Eq. (1). After it is obtained, the throughput is obtained by using the measured results (shown in Fig.

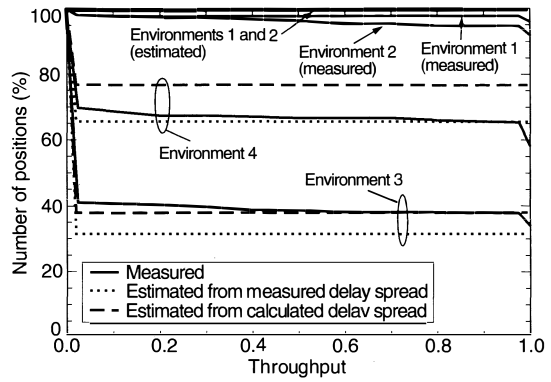


Fig. 15 Measured and estimated throughput characteristics of wireless LAN for environments 1 through 4.

14).

As shown in Fig. 14, the average throughput decreases once the BER reaches 10^{-3}. In many cases the throughput is about 0.0 when the BER is above 10^{-3}. Moreover, the throughput has a polar characteristic (it is either 0 or 1), as shown in Fig. 12. Therefore, throughput S can be assumed when the measured BER is equal to the average irreducible BER as follows.

$$S = \begin{cases} 1, & P_b \leq 10^{-3} \\ 0, & P_b > 10^{-3} \end{cases} \tag{2}$$

The throughput estimated using Eqs. (1) and (2) is shown with the measured throughput in Fig. 15. The throughput was estimated by using the measured or calculated delay spread (shown in Fig. 9). The vertical axis shows the percentage of measurement positions (x=2 to 8 m) at which the throughput was at or above the value shown on the horizontal axis, the same as in Fig. 11. The estimated throughput agreed with the measured values within 10% of the number of positions for all cases. These results show that using the delay spread is a valid and effective way of estimating the throughput characteristics of a wireless LAN.

The throughput and BER of the wireless LAN changed at intervals of several cm when the walls were made of a high-reflection-coefficient material, and estimation of these characteristics at each point was difficult. Still, by using this method, we were able to estimate the number of positions meeting a certain throughput rate.

6. Conclusion

We investigated the propagation characteristics and performance of a 2.4-GHz ISM-band wireless LAN operating in an indoor environment common to Japanese offices. We used a booth in which the ceiling, floor, and wall materials could be changed. The measured results were compared with the calculated ones by using the ray tracing method. Our findings were as follows.

(1) The propagation characteristics can be estimated by using the ray tracing method because the calculated trans-

mission loss agreed with the measured loss within about 5 dB and the calculated delay spread agreed with the measured spread within 10 ns for all environments.

(2) The throughput and BER characteristics decreased and the throughput was 0.0 at over 30% of the positions along the centerline of the booth when the walls were made of high-reflection-coefficient material.

(3) The throughput varied between a BER of 10^{-4} and 10^{-2} depending on the room construction and was almost 1.0 when the BER was below 10^{-4}. The throughput showed especially marked deterioration when the BER reached 10^{-3}.

(4) The number of positions meeting a certain throughput can be estimated to within 10% of the number measured by calculating the delay spread, which we did by using the ray tracing method.

The calculated results agreed well with the measured results, indicating the effectiveness of this estimation method for designing office buildings.

We plan to use this method to design a wireless LAN system in actual indoor environments in order to confirm its validity.

Acknowledgments

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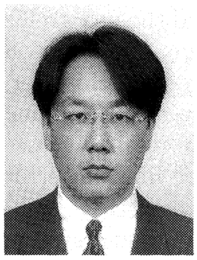

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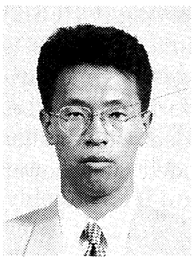

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